3 INTERFEROMETERS: THE TELESCOPES OF THE FUTURE

Answering the scientific questions that will be posed by astronomers in the next millennium will require observatories with larger collecting areas and higher angular resolution than are feasible today. SIM will open the road to extremely high angular resolution — and the solution will be fully scalable to much larger instruments. The mission will further demonstrate synthesis imaging and nulling in preparation for Terrestrial Planet Finder.

The Keck Interferometer, with its four outrigger telescopes, is currently under construction on Mauna Kea in Hawaii. (Artist's concept.)

Scalable Dilute Apertures

All telescope designers attempt to optimize two parameters for a specific observatory: light-collecting power and resolution. Imaging faint distant objects such as young galaxies requires high light-collecting power, equivalent to large collecting areas. Discerning fine details in an image, or measuring precise positions of celestial objects, on the other hand, requires high angular resolution. In conventional filled-aperture telescopes, these two parameters are inseparable. Use of a single monolithic mirror, or a segmented mirror (a set of smaller mirror segments held in the same shape as the equivalent larger aperture), defines both the sensitivity and the angular resolution of the telescope.

The technological approach in the SIM design is, in a sense, to generalize the segmented-mirror concept to dilute apertures. This approach allows designers to control collecting power and angular resolution independently and makes smaller designs fully scalable. A dilute aperture can be constructed using smaller separated telescopes and combining the light coherently to form an image. The angular resolution can be increased by simply increasing the separation of the telescopes. Interferometry is the technique of combining coherently the light from these separate pieces of glass. Optical observers are now developing this technique to make several small telescopes behave like one giant aperture, and several ground-based instruments are in operation. SIM will be the first of a new generation of space-based telescopes that will use dilute apertures.

SIM

SIM will lay the foundation for a broad range of future instruments by the sheer virtue of building the first long-baseline optical interferometer in space. Areas of essential progress are:

- Precision deployment of a structure designed for distributed optics
- Optical control systems on a spaceborne platform; e.g., alignment and steering mirrors, etc.
- Space-based laser metrology with relative precision in the range of tens of picometers
- Control of vibration in a lightweight structure through active and passive damping and isolation of disturbance sources
- Control of interferometric delay — the basis for precision astrometry — using angle and pathlength feed-forward
- Interferometric (synthesis) imaging in space, including fringe calibration
- Monitor and control of instrument thermal environment to a level that permits microarcsecond astrometric precision
- Operation of an interferometer in space in an Earth-trailing solar orbit

In the dilute-aperture approach, instruments can be optimized for the type of science desired — by selecting the appropriate size and placement of the individual collectors. Examples of the size and shape that apertures can take in the radio waveband are the "Y" shape of the Very Large Array and the "T" shape of the Owens Valley Millimeter Array. These instruments are optimized primarily for high-resolution imaging of discrete science targets.

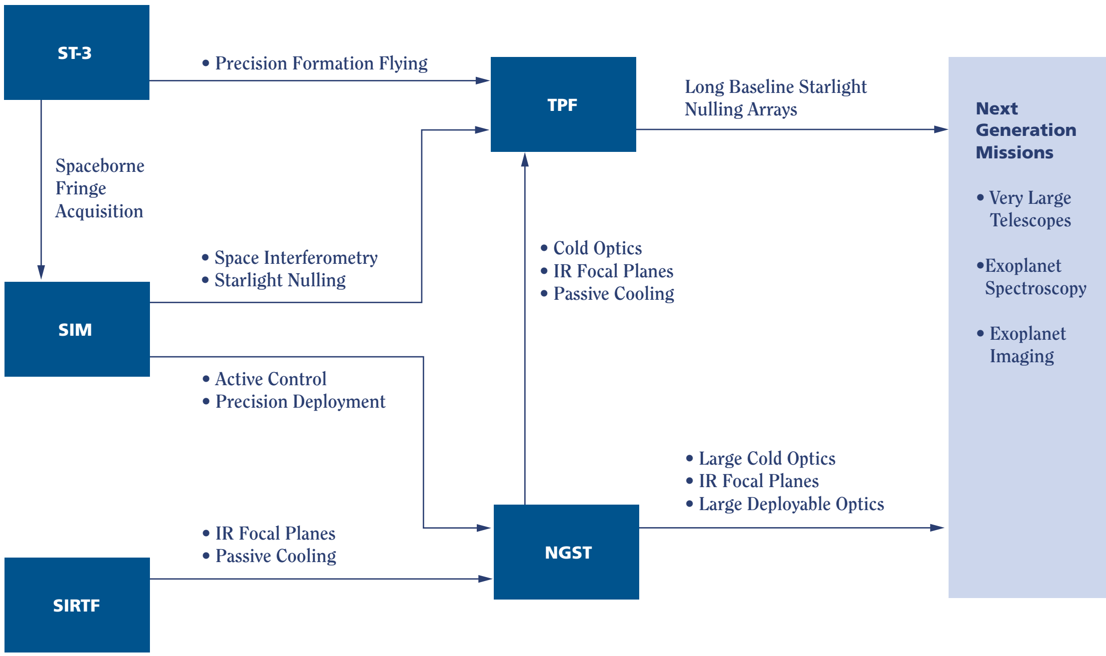
Many of the technologies needed to accomplish SIM's astrometric science are also needed for future missions such as Terrestrial Planet Finder (TPF). But over and above these technologies, which are needed for SIM astrometric science, SIM will demonstrate synthesis imaging and starlight nulling to further fulfill its role as the precursor to TPF. SIM will provide an early opportunity to gain vital experience with these techniques.

Demonstrate Synthesis Imaging

In its synthesis-imaging mode, SIM can provide high-resolution imaging at 10 milliarcseconds — four times higher resolution than the Hubble Space Telescope, albeit with a smaller field of view. The following section highlights some of the opportunities synthesis imaging will provide using SIM. Note, however, that while it is a requirement of SIM to demonstrate synthesis-imaging technology by imaging simple targets such as binary

DILUTE-APERTURE ARRAY

The Owens Valley Millimeter Array (California Institute of Technology) is optimized for imaging in the millimeter waveband. Six individual elements move on rail tracks laid out in a "T" shape.



ORIGINS
Technology development in the NASA Origins Program.

star systems, it is a goal of the project to achieve full (u,v) coverage (subject to fiscal constraints) to allow imaging of more diverse targets — young stellar objects, protoplanetary disks, and black holes in the nuclear region of active galaxies.

The Nuclear Regions of Nearby Galaxies

Do all nearby galaxies harbor black holes in their nuclei? Do the nuclear regions of galaxies grow by eating small galaxies? How do nuclear jets arise? How do stars and gas clouds meet their fate as they swirl around, and are ultimately consumed by the massive black holes thought to live in galactic nuclei? These are questions arising from extensive programs of study with the Hubble Space Telescope over the past 5 years. We have reached the limit of HST resolution for these objects, and the questions have been sharpened — but in many cases the answers remain elusive. There is a strong suspicion that answers may be found if we could image these regions in more detail. SIM will address these questions by imaging the complex, high-brightness central regions of nearby galaxies with more than four times the resolution of HST. SIM's 10-milliarcsecond resolution at 500 nanometers corresponds to 1 parsec at a distance of 30 megaparsecs, rendering the nuclei of all the nearby galaxies open to a degree of detailed scrutiny far beyond what has been possible up to now.

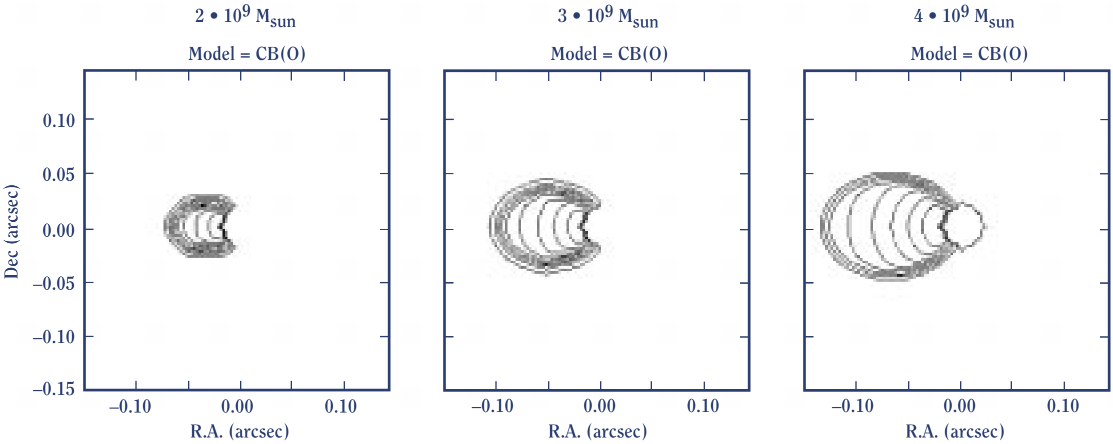
For example, SIM is an extremely precise balance scale for weighing black holes. This feat is accomplished as follows. The matter swirling around a black hole forms a disk containing highly ionized gas. The kinematics and distribution of this gas can be observed in SIM's various spectral channels. These disks are very small, but often very bright, and the shapes of their images in one spectral channel of SIM change rapidly, depending on the disk's rotational speed. The rotational speed depends, in turn, on the gravitational pull of the central mass. In a simulation of the effects of the putative black hole in the nucleus of the nearby Virgo elliptical galaxy M87 on its surrounding disk of ionized gas, SIM can discern the shape of the disk and provide a quantitative measure of the brightness distribution — thus allowing observers to determine the mass of the black hole.

TOPIC	**PROTOTYPES**	**SURFACE BRIGHTNESS V_{mag}/arcsec^2**	**KEY QUESTIONS**
Multiple nuclei in normal galaxies	NGC 4486B, M31	14.3,13.5	How common are they? How do they arise? Are they the result of galactic cannibalism or merging black holes? How do they evolve?
Nuclear cusps, Seyfert and Liner galaxy cores	NGC 3998	11.8	How far into the center does the light cusp go? Is it consistent with a massive black hole? Do all these galaxies have such cusps deep in central regions?
Nuclear emission-line disks, active galactic nuclei narrow-line regions	NGC 4261, M87	2×10^{-13} erg/cm^{-2}/s^{-1}/ arcsec^{-2} Hα, Hβ,& OIII emission-line imaging	Are there nuclear black holes in all galaxies? What are their masses, and do bigger host galaxies have bigger black holes?

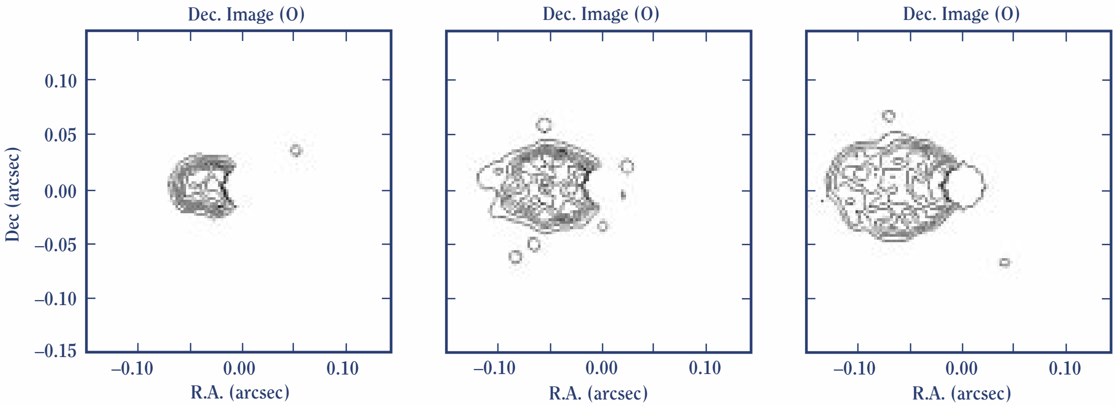
GALACTIC NUCLEI

The prototypes have been studied by HST and are expected to have underlying structure not resolvable with HST.

Model Source



Reconstructed Image After 200 Iterations



Demonstrate Nulling

Nulling is the technique used to reach the challenging scientific goal of studying a faint object that lies within the glare of a nearby bright object. Nulling can be regarded as the interferometry analog of a coronagraph on a conventional telescope — they share the objective of studying faint objects next to bright ones. However, an interferometer offers, in principle, greatly enhanced rejection of the bright object, and hence better performance in detecting faint companions.

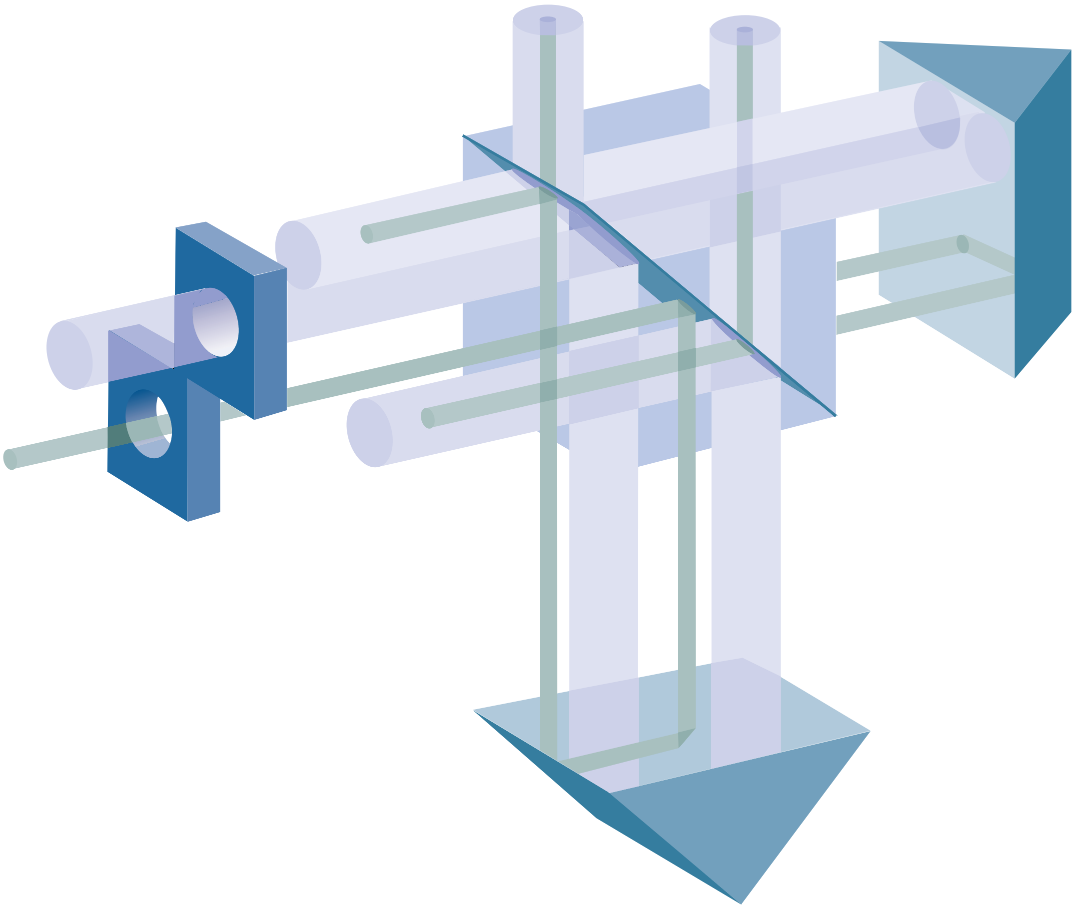
Nulling was first proposed by Ronald Bracewell as a technique for the direct detection of Jupiter-like planets in the mid-infrared waveband. The basic concept is to put additional path delay into one arm of the interferometer, equivalent to a 180-degree phase shift. Instead of the usual bright fringe, this places a "dark" fringe on the detector where the bright star would be. This particular implementation produces a "deep" null only at a particular wavelength — where the extra delay produces an exactly 180-degree phase shift.

A nulling interferometer uses most of the same hardware as a conventional Michelson interferometer. The main difference is in how the two beams from the collector are combined. SIM will have three "normal" astrometric beam combiners and a fourth (nulling) beam combiner. SIM's achromatic nulling beam combiner is illustrated in the accompanying figure; in the illustration, the light path on one side of the beam combiner comprises reflections out of the plane of the figure.

SIM will use nulling for scientific investigations, but the nulling capability is driven primarily by the need to demonstrate this critical technology for TPF. SIM will provide the experience of operating a nulling beam combiner in orbit. Even though the TPF design is preliminary, requirements on the nulling performance can be derived through arguments that do not depend on those details. The key design parameter is the starlight suppression ratio, or null depth, which SIM will demonstrate to a level of 1 part in 10,000.

The performance requirements for nulling on SIM are summarized in the table below. Given a λ^{-2} scaling between the operating wavelengths of TPF and SIM, the derived requirement for SIM is a null depth of 10^{-4} at 1 micrometer. The most important component is control of phase jitter, but a number of other effects also cause "leakage" of light from the central star reaching the detector. Leakage terms are not statistically independent, but

BLACK HOLE IN M87
(opposite) Simulated SIM synthesis-imaging data of the effects of the black hole in M87 on its surrounding disk of ionized gas. The disk has been inferred from observations by HST, but has not yet been observed directly. Three different masses for the black hole are modeled.



NULLING BEAM COMBINER

Optical layout of the SIM achromatic nulling beam combiner.

are cumulative. The two interfering wavefronts must match to a very high degree — on the order of λ/1,000. The crucial factor is that the phase difference must be 180 degrees, not just for the average phase between the two interfering beams, but everywhere along the wavefront. Hence, the null depth is set by the sum of the leakage terms.

In practice, maintaining λ/1000 wavefront quality is impossible at visible wavelengths over the entire optical train of SIM, and some way is needed

SOURCE	LEAKAGE	ORIGIN
Phase jitter	3×10^{-5}	0.8 nm rms optical path jitter
Pointing	3×10^{-5}	0.025 arcsec rms pointing
Amplitude match	1×10^{-5}	0.06% intensity match between two arms
Polarization rotation	1×10^{-5}	0.36 deg differential rotation
Polarization shift	1×10^{-5}	0.72 deg differential delay
Reserve	1×10^{-5}	—

NULLING
Performance requirements for nulling on SIM.

for “cleaning up” the wavefront before the light hits the detector. Both SIM and TPF will use spatial filters to achieve this. For SIM, the filter will be a single-mode fiber, a technique that has been used successfully in ground-based instruments such as the Palomar Testbed Interferometer. On the ground, the motivation for using fibers is to eliminate some of the wavefront irregularities imposed by the atmosphere. Even though some light is rejected and does not propagate through the fiber to the detector, the fringe visibility and overall signal-to-noise ratio can be greatly improved. This is because the filter selects only those portions of the wavefront that are fully coherent.

Protoplanetary Disks and Planet Formation

SIM’s nulling capability will enable researchers to address questions such as these: How do very young stars form out of the disks of interstellar matter that are thought to be the stars’ progenitors? How do the stars grow in mass? How do planets form in the swirling dust clouds that envelop many stars? What is the structure of these clouds, and can we see clues in these clouds for the birth of new planets? SIM’s 10-milliarcsecond resolution corresponds to 10 AU at a distance of 1 kiloparsec, so solar-system-size regions around the nearby stars are open to detailed study with SIM. The price for nulling is that the images are always symmetric about the center of

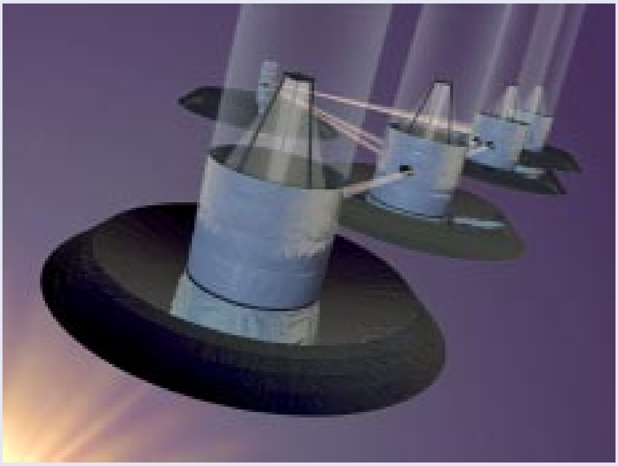
The Terrestrial Planet Finder (TPF) will study planets beyond our own solar system in a variety of ways — from their formation and evolution in the disks of newly forming stars to the properties of planets orbiting the nearest stars; from their number, sizes, and locations to their suitability as abodes for life. By combining the sensitivity of spaceborne telescopes with the high spatial resolution of an interferometer, TPF will be able to reduce the glare of parent stars by a factor of more than 10^5 to reveal planetary systems as far away as 15 parsecs or 45 light-years. In addition to determining the size, temperature, and orbital location of planets as small as Earth in the habitable zones of distant solar systems, TPF's spectroscopic capabilities will allow atmospheric chemists and biologists to use the relative proportions of gases like carbon dioxide, water, ozone, and methane to assess whether a planet someday could, or even presently does, support life.

TPF Properties

Telescopes	Four × 3.5 m diameter; diffraction-limited at 2 μm, operating at 40 K
Baseline	50–1,000 m (free-flying)
Angular resolution	0.75 milliarcsec (at 3 μm with 1,000-m baseline)
Wavelength range	7–17 μm for planet detection; 3–30 μm for general imaging
Field of view (determined by primary telescope beam)	0.25″ at 3 μm; 1.0″ at 12 μm
Spectral resolution	R~3–20 for planet detection and spectroscopy; R~3–300 for continuum and spectral-line imaging
Sensitivity	0.35 μJy at 12 μm (5σ in 10^4 s at R~3)
Orbit	Earth-trailing (SIRTF) or L2
Mission duration	>5 years
Mission launch	2011

TPF will advance our understanding of how planets and their parent stars form. Current observations show that the disks of forming stars are tens to hundreds of astronomical units across, but we know almost nothing about the inner regions of forming planetary systems — where planets are thought to be evolving. TPF will resolve disk structures on the scale of a few tenths of an AU to investigate how gaseous and rocky planets form out of accreting disk material. By studying emissions from dust, ices of water and carbon dioxide, and gases such as carbon monoxide and molecular hydrogen, TPF will investigate whether, as theory predicts, rocky planets form in warmer regions and gaseous planets in colder regions of a nascent solar system.

Finally, TPF can investigate many other astrophysical sources where observations of milliarcsecond structures are critical to understanding the essential physical processes. Combining the sensitivity of the Next Generation Space Telescope (NGST) with milliarcsecond imaging — demonstrated by SIM — will enable detailed studies of the winds from dying stars that enrich the interstellar medium with heavy elements, and the cores of active galaxies from our own Milky Way to ultraluminous objects at high redshift.



Terrestrial Planet Finder. *Architecture in which the collectors are free-flying, allowing the baseline length to be optimized for planet searching toward a number of different target stars. (Artist's concept.)*

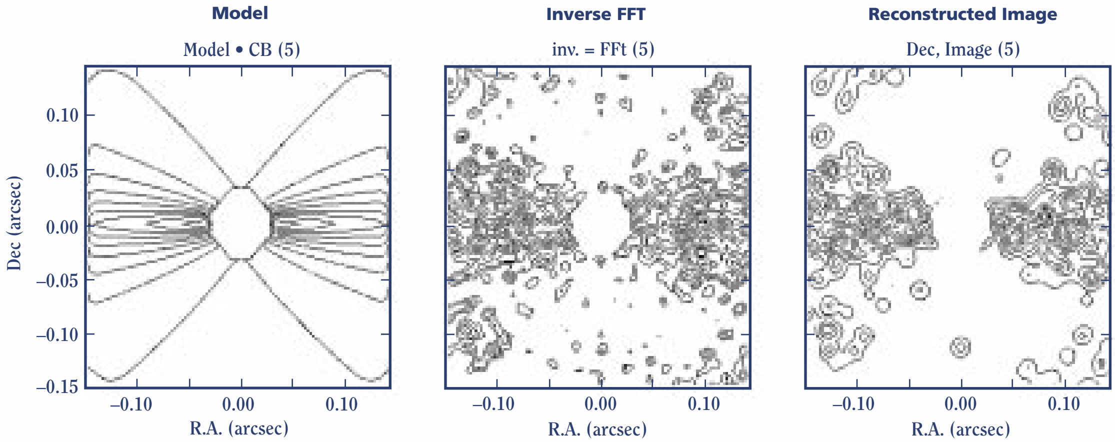
the field of view, but this is acceptable for accretion and dust disks around stars, since such symmetry is expected. This feature of SIM, coupled with its very high angular resolution, enables new observations to be made of accretion disks around newly forming stars, and of protoplanetary disks around more mature stars such as the Sun. Such studies started with the Hubble Space Telescope, but the limited angular resolution and the difficulty in blocking out the glare from the parent star prevented work on all but the nearest and largest systems.

An example of this capability may be found in the results of modeling a "zodi" disk system similar in structure to the Earth's zodi disk, but 100 times brighter, located around a solar-type star at a distance of 500 parsecs. SIM will not be sensitive enough to study faint zodi disks such as that in our own solar system, but so little is known about these systems that fundamental studies of the general structure of such disks still remain to be done. Our simple model disk is smooth, without a central hole or gaps at some radii. The left panel of the figure shows the input model, the middle panel shows the direct Fourier inversion, and the right panel illustrates the reconstructed image after 200 iterations of restoration with the maxi-

IMAGING TARGETS

Protoplanetary disk imaging targets for SIM.

TOPIC	PROTOTYPE	TYPICAL SURFACE BRIGHTNESS	KEY QUESTIONS
Dust disks around main-sequence stars	Beta Pic	12–15 mag/arcsec^2	Do the radial surface brightness distributions show gaps indicating the presence of planets?
Young stellar object disks	GM Aur	~15	How do stars form disks?



mum-entropy algorithm. The central region is masked out (after the simulation) to better show the extended, low-level contours. Note that the images are centrally symmetric, a consequence of operating SIM in nulling mode. No attempt has been made to optimize this restoration; however, the general form of the dust disk is already clear, and the distribution of dust density can be obtained. The unique combination of imaging with a nulling interferometer will permit SIM to image distant zodi disk systems if they have at least 100 times the solar dust content, and SIM can do this in a few hours for stars at distances of several hundred parsecs.

ZODI DISK MODEL

Simulation of an edge-on view of a bright exozodi disk at a distance of 500 pc, as observed with SIM in nulling-imaging mode.